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UWB-over-Fibre in Next-generation Access Networks

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1. Introduction

The access network is the part of the telecommunications infrastructure responsible for the connectivity in the last mile, i.e. from the operator's Central Office or Exchange to the customer premises. At the Central Office the access network interfaces with the metropolitan or with the core optical networks, which aggregate and routes the data from a large number of users. At the customer premises, the access network extends the connectivity to the so-called user network. Different user network implementations can be found nowadays: LAN (Local Area Network), PAN (Personal Area Network), HAN (Human Area Network) or even BAN (Body Area Network). A combination of some of these can be present in a given usage scenarios.

Different usage profiles must be accommodated in the access network: a residential user, a small-office, or even a large company - all these exhibit very different connectivity requirements- leading to different technological implementations. Currently deployed access networks are based on copper twisted-pair transmission media and are deployed over legacy telephone networks. This is, by example, the case of ADSL (Asymmetric Digital Subscriber Line).

Access networks based on legacy infrastructures are reaching their capacity limits. The conventional access network infrastructures, namely the twisted-pair telephony networks and the coaxial Cable Television (CATV) networks, struggle to support current data traffic demands for high-definition content distribution and real-time applications. Digital Subscriber Line (DSL) techniques and cable modem techniques evolved into higher speeds, but at the cost of a shorter reach. Currently, the unique properties of optical fibres (e.g. low losses and extremely wide bandwidth) have made them the ideal candidate to meet the capacity challenges for now and the foreseeable future (Koonen, 2006). The access network based on optical fibre is called fibre-to-the-home (FTTH). FTTH networks transport baseband data modulated in one or several optical carriers (laser lights) at different wavelengths.

FTTH networks are largely under deployment nowadays (Japan Today, 2008). FTTH access is a flexible, future-proof access technology that enables the provision of Gb/s bitrates per user. FTTH is already being commercially offered in countries like Japan. However, FTTH deployment is a very expensive investment. For example, the Spanish incumbent operator Telefonica has recently announced a €1bn programme to deploy FTTH in Spain. In UK, BT is currently running a £1.5bn programme (recently announced, March 2009) to deploy optical access to 10 million UK homes (40%) by 2012 (Jackson, 2009).

Several studies point out that FTTH will become the key differentiator between competing operators (FTTH Council, 2009; Saorin, 2009). In addition, FTTH is the only technology capable of creating new revenue streams from high-bitrate applications, e.g. high-definition entertainment (HD-video, HD-games, etc). Another advantage to FTTH is that permits better operational efficiencies compared with other access technologies, primarily by reducing maintenance and operating costs. Also, FTTH tends to require smaller central offices, and exhibits lower energy consumption. Next-generation optical access networks (Kazousky et al., 2007) is an step-forward over current FTTH technology. Next-generation optical access must support advanced telecommunications services requiring high bitrate provision to an ever increasing number of users. The access network topology, configuration and functionalities will evolve driven by high-bitrate demanding services like high-definition video, 3-D video, on-line gaming, cloud storage and cloud applications and, of course, Internet browsing of complex webpages. Video or multimedia transmission accounts today for a large percentage of the data transmitted in the access network (Werbach, 2009). Video coding technology is evolving optimising the performance and permitting an effective bitrate reduction in single-digit percentages year-after-year (Etoh et al., 2005). Nevertheless, it is difficult to assure that this coding gain could be sustained in the long term to compensate the data traffic originated in multimedia transmissions (Pyramid Research, 2010). Effectively, the network infrastructure must evolve to accommodate higher bitrates for a larger number of users, i.e. to increase the overall network capacity.

Moreover, in order to satisfy these higher data rates requirements, new techniques for the integrated distribution of wireless communication signal are required. These techniques must facilitate the deployment of an integrated access network at the customer premises, enabling the integration of optical transmission over an optical access network and radio-frequency transmission in the same infrastructure.

In conclusion, three important paradigms should be addressed in next-generation optical access networks:

- Spectral efficiency leads the overall network capacity expansion. The conventional strategy to increase the network capacity relies on deploying more fibre or transmission equipment. Advances in the processing/cost ratio of modern digital signal processors (DSP) and field-programmable gate arrays (FPGA) integrated circuits indicate that a shift from raw transmission equipment to advanced modulations based on very fast data processing is expected. Advanced modulation schemes permit higher spectral efficiency ratios, measured in bit/s/Hz. Updating the programmatic code implemented on these integrated circuits is a less expensive solution compared to the deployment of new transmission equipment on the field.
- Integration of the optical access network and the user radio environment. Optical access becomes the first step to establish the communication with the costumer. The second and last step is the final user radio link. Both optical access and user radio networks must be integrated in order to provide high-performance end-to-end connectivity, from the central office to the user device, including quality of service management.
- Increasing use of commercial off-the-shelf (COTS) electronic equipment. The performance and capabilities of current commercial devices operating wireless technologies make them an interesting option from the operator point of view in order to reduce the deployment cost (CAPEX) and the sustained operational expenses (OPEX).

These three next-generation optical access paradigms can be addressed employing ultra-wideband (UWB) technology. UWB technology is already one of the most promising

techniques for the user wireless networks due to tolerance to multi-path fading, low probability of interception and high-bitrate capabilities (Llorente et al., 2008). Nowadays, market applications of UWB aim to high bit-rate wireless communications at picocell range, namely as a replacement of high definition (HD) video/audio cabling (Morant et al., 2009a) among others.

The extension of UWB technology to the optical access network in the so-called radio-over-fibre configuration permits the transmission of UWB signals in their native format through fibre-to-the-home (FTTH) access networks. This approach exhibits several advantages:

- i. FTTH networks provide bandwidth enough to distribute a large number of UWB signals, as each one of them can occupy up to 7.5 GHz in current UWB regulation (FCC, 2002).
- ii. No trans-modulation is required at user premises. HD audio/video content is transmitted through the fibres in UWB native format.
- iii. No frequency up-conversion is required at customer premises. The UWB signals are photo-detected, filtered, amplified and radiated directly to establish the wireless connection.
- iv. FTTH networks are transparent to the specific UWB implementation employed. This flexibility is of special interest for operators as UWB regulation is still evolving.

Hence, UWB radio-over-fibre is a rapid and cost-effective solution to deliver HD content in FTTH access networks with further wireless PAN (WPAN) transmission in home. FTTH passive optical network (PON) architectures are cost efficient compared with architectures including amplification and regeneration stages in the field, and are supported by a set of mature international standards (G/E-PON) (Prat, 2008). Current standard PON based on time-division multiple access (TDMA) are expected to evolve toward PON based on wavelength division multiplexing (WDM-PON) to keep up with the requirements of future access networks regarding the aggregated bandwidth.

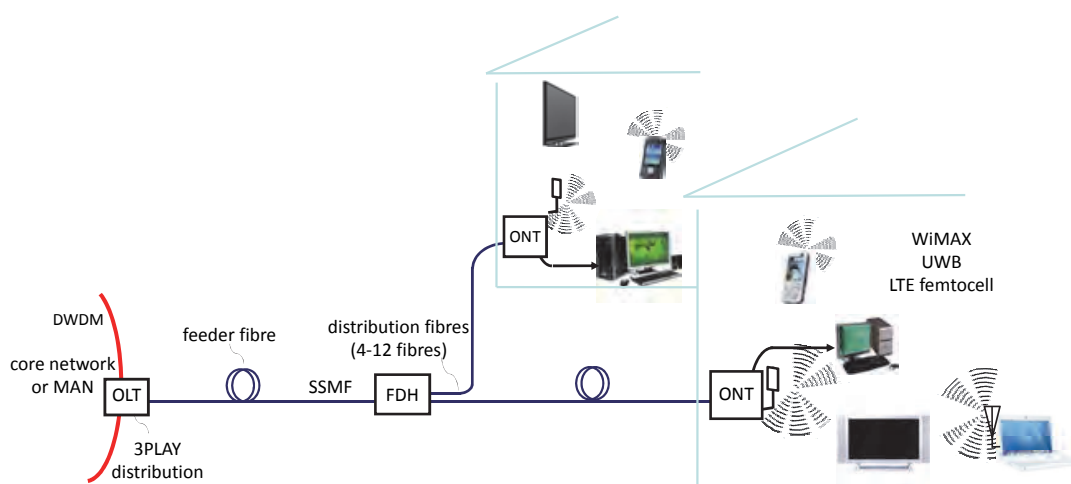
UWB is a radio technology capable of providing multi-Gbit/s short-range indoor communications. UWB uses regulated spectrum from 3.1 to 10.6 GHz with a minimum signal bandwidth of 500 MHz (or 20% fractional bandwidth) (FCC, 2002). UWB presents the unique characteristic of being designed for coexistence with other licensed or unlicensed services in the same frequency range. This is achieved limiting the equivalent isotropic radiated power (EIRP) density to -41.3 dBm/MHz and introducing detection-and-avoid (DAA) mechanisms (WiMedia, 2009b; ECC, 2008). UWB operation in the 60-GHz band is an open opportunity to provide potential data rates of >3 Gbit/s worldwide (Beltrán & Llorente, 2010a). The EIRP limit constrains UWB radio to WPAN. There is a large market availability of UWB devices addressing wireless peripheral inter-connection and HD audio/video streaming functionalities (Alereon, 2009; Wisair, 2010). These devices are based on the multi-band orthogonal frequency-division multiplexing (OFDM) implementation as defined in the ECMA-368 standard (ECMA, 2008a). Maximum capacity in actual UWB equipment is 480 Mbit/s per band. This gives a maximum overall capacity of 6.72 Gbit/s per user when fourteen bands are combined. This capacity is supported in single-chip UWB solutions (Alereon, 2009). In addition, the impulse-radio UWB implementation is capable of providing simultaneous communications and high-resolution ranging (Dardari et al., 2009).

At this point, multi-service coexistence with other wireless signals is an important factor in optical transmission. With the recent introduction of radio standards such as WiMAX or LTE the coexistence issues appear as a possible issue. From one side, WiMAX is considered as an effective but challenging approach to extend IPTV services in the wireless and

mobility dimension, and from the other, LTE in femtocell applications is expected to become an important part of next-generation cellular networks.

Fig. 1 shows the network architecture integrating the complete optical path (FTTH and in-building distribution network) and also the user radio path for a converged service provision. The network provides triple-play services. HD content is provided by UWB, LAN connectivity is provided by WiMAX, and cellular phone connectivity is provided by LTE. This architecture permits a centralized network management strategy to be used in the LTE, WiMAX, and UWB terminals in a given user area.

In addition, UWB in the 60-GHz band has been reported as a very interesting approach for next-generation integrated PON-radio systems (Beltrán et al., 2011) and for interference-sensitive scenarios like on-board plane equipment (Beltrán & Llorente, 2010a). 60-GHz UWB systems would benefit from the unlicensed worldwide availability of the 60-GHz band together with the maturity and intrinsic coexistence characteristics of UWB technology. 60-GHz radio is about to become easily available for consumer applications and permits secure multi-Gbit/s wireless communications with reach exceeding typical WPAN.



MAN: Metropolitan area network. OLT: Optical line terminal. ONT: Optical network terminal. SSMF: Standard single-mode fibre. FDH: Fibre distribution hub. DWDM: Dense wavelength division multiplexing

Fig. 1. Integrated FTTH and in-building optical and radio transmission of triple-play radio

Optical techniques are critical for future-proof, versatile and high-capacity service provisioning via UWB-over-fibre in optical access networks. Optical techniques can also benefit from the well-known advantages offered by microwave photonics devices, such as light weight, small size, and immunity to electromagnetic interference (Capmany & Novak, 2007).

1.1 Next-generation access networks

FTTH network architectures are the foundation of next-generation optical access. In practice, many access technologies are commonly referred to as FTTx when in fact they are simply combinations of optical fibre and twisted pair or coaxial cable networks. This has created some confusion though as FTTx covers several different architectures and protocols. In fact, some of Digital Subscriber Lines (DSL) and Hybrid Fibre Coax (HFC) networks have been qualified as FTTx networks due to their use of fibre in the access, as a PON does. Hence, it is best when referring to a deep fibre penetration network to specify its actual architecture. The most

common architectures are: Fibre-to-the-Home (FTTH), Fibre-to-the-Building (FTTB), FTTCurb (FTTC) and FTTNode (FTTN) (Kunigonis, 2009).

Fibre-to-the-premises (FTTP) is a term used in several contexts: as a blanket term for both FTTH and FTTB, or in the cases where the fibre network includes both homes and small businesses. Each of these has a different physical architecture as depicted in Fig. 2, and its main characteristics are described below:

- FTTH pushes fibre all the way to individual residential wells. FTTH is completely absent copper in the outside plant and provides at least 30 Mbps service, but due to the inherent characteristics of optical fibre can provide literally infinite bandwidth.
- FTTB typically uses the Point-to-Point (P2P) architecture in the outside plant providing a dedicated fibre to each building or block of buildings. The fibre is terminated at a Remote Terminal (RT) which is an active device requiring powering and security typically located in the basement, communications room or utility closet. Usual FTTB applications have been providing at least 10 Mbps. If twisted pair is installed to provide requirement bandwidth services it can reach up to 50 Mbps.
- FTTC, also called Fibre-to-the-Cabinet (FTTCab), extends fibre to a street-side cabinet or Digital Loop Carrier (DLC). Typically uses ADSL2 technology pushing fibre 150-700 m from the subscriber terminating at a RT.
- FTTN is similar in architecture to FTTC except that the RT is positioned much further from the subscribers up to 1500 m and can serve 3-500 subscribers. Both utilize existing twisted pair outside plant to connect to the customer. In this case, bandwidth is dictated by two factors: DSL technology and copper loop length.

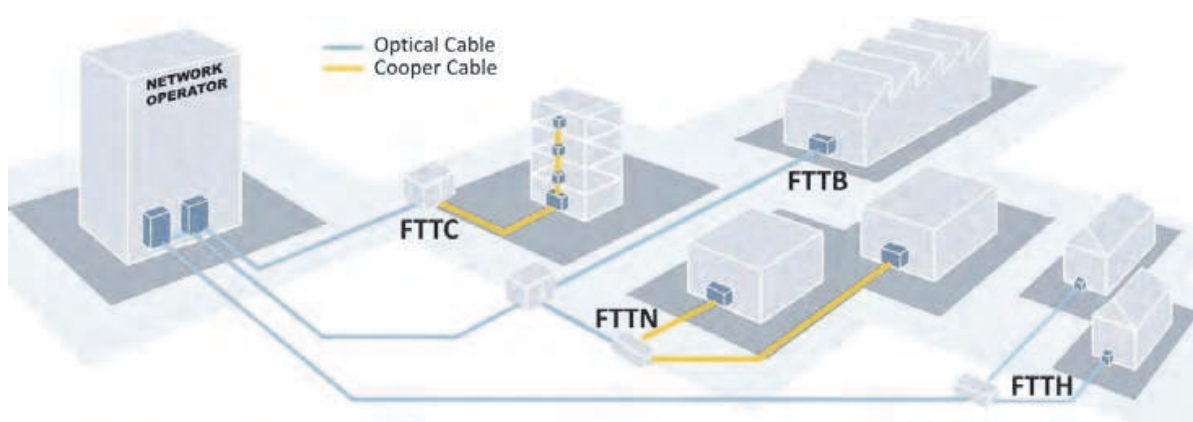


Fig. 2. FTTx Deployment

Signals over copper are significantly degraded over long distances directly affecting the bandwidth capacity. In the most extreme conditions (4-5 km) some customers may not even be able to be served by DSL. In some cases the carrier will use both twisted pairs to boost the bandwidth throughput. Due to shorter copper loop lengths in a FTTC network the operator has improved scalability from a bandwidth perspective.

Fibre penetration directly correlates to the bandwidth throughput of each defined architecture and therefore the service capability for the operator. The bandwidth requirements of each network operator differ but all are growing. Fibre penetration is also an indicator on the CAPEX and OPEX expected. Deep fibre will result in a higher CAPEX for existing neighbourhoods, but is actually near cost parity with all architectures for new builds. Deep fibre will deliver the maximum amount of OPEX savings comparably.

FTTH enables the delivery of savings due to reductions in cost for network, central office and outside plant operations as well as customer service. Network reliability dramatically increases as well with FTTH ensuring a steady stream of revenue and enhanced customer satisfaction (Kunigonis, 2009).

1.2 State-of-the-art of radio-over-fibre systems

Wireless communication has been experiencing phenomenal growth for some time. It is now the fastest growing sector of the telecommunications industry. While voice and low bit-rate data were the main wireless services in the past, the focus of today's wireless networks has clearly shifted towards high bit-rate data services. The proliferation of WiFi hotspots and the introduction of new cellular systems (such as 3G, LTE, and HSPA) and other high-data-rate wireless systems such as WiMAX (IEEE 802.16e) are some examples. With the advent of popular bandwidth services such as HD video or on-line gaming, these and other wireless systems are under pressure to offer higher data speeds in order to enable the delivery of such services to the ever increasing number of wireless users.

Some ways of increasing the data throughput to the wireless users are: using antenna diversity through multiple-input-multiple-output (MIMO) system configurations, greater RF bandwidth or smaller radio cells. As the radio channel is a shared medium, wireless users end up competing for bandwidth in any given radio cell. By reducing the cell size, the number of users sharing bandwidth may be reduced, thereby considerably increasing the share of the average data throughput available to each user in the cell. However, this approach of deploying small radio cells leads to a tremendous increase in the density of the required radio access points. This presents significant challenges in terms of the extensive feeder network required to interconnect the large number of radio access points (antennas) (Sauer et al., 2007). For this reason, the capacity of the wireless system is ultimately dependent on the utilized RF bandwidth. The ISM band frequencies at 2.4 and 5-GHz are severely congested with a multitude of consumer products using those frequencies. Therefore, the most promising path towards high-data rate (Gbit/s) wireless communication is to migrate to higher carrier frequencies, which offer much more bandwidth (Razavi, 2008). For instance the FCC has set aside 7-GHz contiguous bandwidth for wireless data communication in the 60-GHz band (57 – 64-GHz).

Radio-over-fibre technology has long been proposed as an effective way to deal with the demands of small-radio-cell networks (Sauer et al., 2007). This chapter discusses the use of this technology in using UWB-over-fibre techniques in the 3.1-10.6-GHz and in the 60-GHz band.

2. UWB-over-fibre performance in optical access and in-building networks

Radio-over-fibre transport of UWB wireless signals, i.e. radio transmission over a shared optical media fibre, is a rapid and cost-effective solution to extend the UWB radio range to in-home, in-building or even wide area applications. The application scenario in this case is UWB range extension.

Two major UWB implementations are mainstream nowadays: OFDM-based and impulse-radio. The compared performance of the two UWB implementations along different optical access fibre links was demonstrated in the literature (Llorente et al., 2008). The experimental results demonstrate the feasible distribution of 1.25 Gbit/s UWB signals achieving BER operation of 10^{-9} at 50 km with both IR-UWB and OFDM-UWB implementations where impulse-radio UWB is more affected by the frequency response of the electrical devices.

The in-building network distribution performance was evaluated in (Beltrán et al., 2009). Comparing impulse radio and OFDM UWB it is observed that impulse-radio UWB requires less optical launched power than its OFDM-UWB counterpart for successful standard single-mode fibre (SSMF) transmission over a distance of 300 m. In the case of in-building distributions different optical media can be employed, such as multi-mode fibre (Beltrán et al., 2009), plastic optical fibre (POF) (Lethien et al., 2009) or bend-insensitive optical fibre (Beltrán et al., 2011).

The spectral efficiency in these systems can be maximised by the distribution of polarization-multiplexed UWB (PM-UWB) signals is a suitable technique for the provision of wireless connectivity to a large number of users. This approach provides a higher spectral efficiency and the user capacity is doubled compared with UWB on a single wavelength. The maximum transmission reach of the proposed PM-UWB technique has been investigated in (Morant et al., 2009b) demonstrating successful transmission of 1.2 Gbit/s OFDM-UWB signals with 0.76 bit/s/Hz spectral efficiency at PON distances up to 25 km.

3. Multi-service coexistence with UWB

With the recent introduction of radio standards as Mobile WiMAX or LTE the coexistence issues of UWB with other licensed radio signals appear as a possible issue. From one side, WiMAX is considered as an effective but challenging approach to extend IPTV services in the wireless and mobility dimension, and from the other, LTE in femtocell applications is expected to become an important part of next-generation cellular networks. UWB coexistence with WiMAX and LTE is herein addressed.

The most important similarity between UWB, LTE and WiMAX is the OFDM signalling. LTE and WiMAX technologies also employ Viterbi and turbo accelerators for further error correction. From the viewpoint of chip designer view, it is possible to reuse gates if you have to support both schemes in the same chip set. For these reasons, recently it has been proposed to provide triple-play services, mainly data, voice and video using a simultaneous transmission of WiMAX, LTE and UWB standard signals. In particular, this proposal implies the simultaneous radio-over-fibre transmission of the full standard OFDM signals in coexistence in optical access networks as it can be observed in Fig. 3.

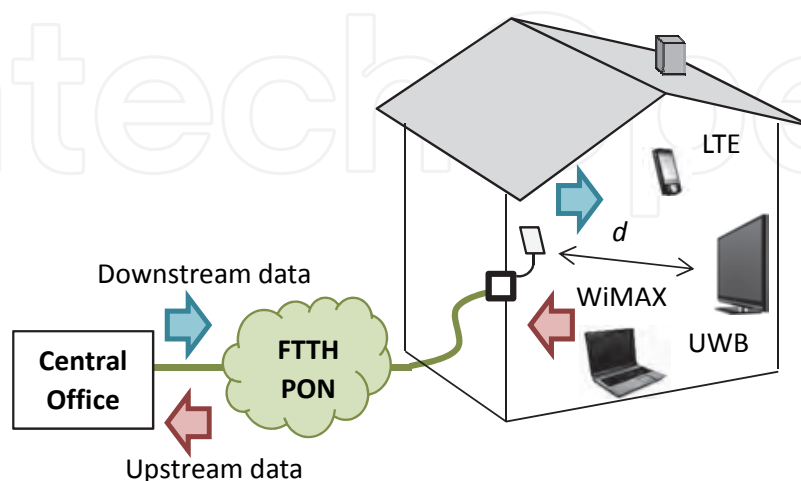


Fig. 3. Application scenario for bi-directional 3PLAY (LTE, WiMAX and UWB) distribution in FTTH access networks and radio propagation at user premises

This provides to the user a higher aggregated capacity and simplifies the overall architecture as it is transparent to the service provided and simplifies the deployment cost at customer premises as no transmodulation or recodification is needed and the different services could be received with standard equipment without additional set-top box.

3.1 Wireless standard overview

3.1.1 WiMAX

WiMAX stands for Worldwide Interoperability for Microwave Access and it is a wireless standard for transmitting data using radio waves. It is a radio technology known as last mile application that allows reception of data by microwave and radio wave transmission. The protocol that characterizes this technology is the IEEE 802.16. One of the main goals of this radio technology is to provide broadband services in areas where the deployment of cable or fibre for the low density of population has a very high cost per user as in rural environments.

WiMAX Forum is the standardization body authorized to certify compliance and interoperability between equipment from different manufacturers, which means that any equipment that does not have this certification, cannot guarantee its interoperability with other products. The profiles of WiMAX equipment that is currently on the market use frequencies of 2.5 GHz and 3.5 GHz.

Currently there are two different mobility profiles contained within the 802.16 standard. One with fixed access (802.16d), which establishes a radio link between base station and user equipment located in the user's home, to the fixed environment. The maximum theoretical speeds that are available are 70 Mbps with a bandwidth of 20 MHz, however, in real environments could achieve speeds of 20 Mbps shared by all the users of the cell with a cell radius of up to 6 km. And a second one with complete mobility 802.16e, which allows the movement of the user in a manner similar to GSM / UMTS.

3.1.2 LTE

LTE (Long Term Evolution) is a 3GPP standard proposed for mobile Internet services like data transmission over 300 meters and high-definition video thanks to OFDM access (OFDMA) technology. The most common frequency band in commercial available devices is 2.6 GHz, but also operates at 800 MHz, 1.5 GHz, 1.8 GHz and 3.5 GHz. The novelty of LTE is that the radio interface based on OFDMA for the downlink (DL) and YSC-FDMA for uplink (UL). The modulation chosen by the 3GPP standard makes the different antenna technologies (such as multiple input multiple output or MIMO) have greater ease of implementation, which improves the performance in even quadrupling the data transmission efficiency.

3.2 Performance evaluation

Following with the radio-over-fibre techniques described in Section 2, polarization multiplexing could be used for the transmission of different radio services in each polarization. This was demonstrated in (Perez et al., 2009) with a simultaneous UWB and WiMAX service provision in two orthogonal polarizations achieving 25 km PON reach with only 2 dB EVM penalty compared with a UWB single-polarization distribution scheme. However the polarization multiplexing technique becomes more complex as the number of services increases, as the orthogonality of the different optical lights is affected. For this reason the coexistence of different radio standards for multiple service provision was further investigated using radio-over-fibre techniques.

In (Morant et al., 2011a) it is proposed and demonstrated the bi-directional radio-over-fibre transmission of triple-format LTE, WiMAX and UWB full-standard OFDM signals in coexistence. Coarse wavelength division multiplexing (CWDM) is employed to map the uplink and downlink optical signals in 1300 nm and 1550 nm respectively. Moreover, the optical-to-radio and radio-to-optical interfaces was investigated in (Morant et al., 2011b) for the triple-play transmission including the wireless transmission at customer premises after the radio-over-fibre distribution through a PON.

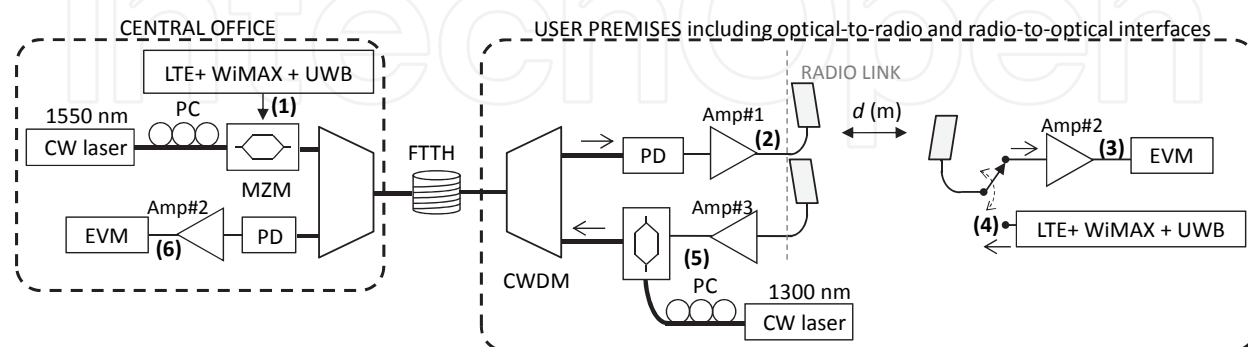


Fig. 4. Block diagram of the experimental setup for the demonstration of triple-play bi-directional UWB-over-fibre transmission

Fig. 4 depicts the experimental setup used for the demonstration of triple-play bi-directional transmission evaluating the optical access performance (connecting point (2) to (3), and (4) to (5)) and the radio performance at customer premises with wireless transmission at different radio distances $d(\text{m})$.

In the optical access evaluation the launch power level of the lasers at both sides of the communication are changed and different lengths of the PON are evaluated in order to emulate a fibre-to-the-home deployment up to 120 km standard single-mode fibre. The triple-play signal comprises: a UWB channel full WiMedia compliant (ECMA-368, 2008a) in center frequency at 3.96 GHz with 528 MHz bandwidth. The LTE and WiMAX signals are generated with two vector signal generators (VSG). The first one generates an advanced LTE signal using frequency division duplex at 2.6-GHz with full-filled 16QAM in 20 MHz bandwidth, and the second one a fixed IEEE 802.16 WiMAX signal at 3.5-GHz using 16QAM in 24 MHz bandwidth. The three standard OFDM signals are combined together and applied to Mach-Zehnder modulators working at quadrature bias point for each 1300 nm and 1550 nm path. Both paths are combined using CWDM splitters and the signal is transmitted through SSF. Signal detection was accomplished using 10-GHz bandwidth

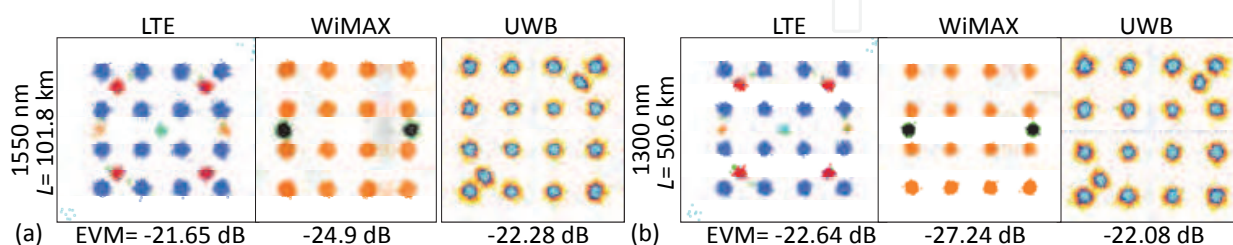


Fig. 5. Received constellations of LTE, WiMAX and UWB at different points of the experimental setup of Fig. 4: (a) after 101.8 km SSMF [Point (2)] for the 1550 nm downstream path, and (b) after 50.6 km SSMF for the 1300 nm upstream path

photodiodes followed by electrical amplification. As it can be observed it is a straight-forward deployment where the signals are only photodetected, amplified and radiated to the final user, without needing any upconversion in frequency or remodulation of the signals. This simplifies the overall scheme and provides transparency to the system, as any other full-standard signal could be transmitted in the same architecture only designing the power levels necessary at the central office.

At both ends of the architecture the error vector magnitude (EVM) of each OFDM standard signal is measured and compared with the maximum EVM limit stated in current regulations: -17 dB for ECMA-368 UWB using dual-carrier modulation (DCM) or -14.5 dB for UWB in QPSK (ECMA-368, 2008a), -24.43 dB for 802.16 WiMAX using 16QAM (IEEE 802.16, 2009a), and -18 dB for GPP LTE using 16QAM (3GPP TS 36.101, 2009).

It is demonstrated that up to 50.6 km SSMF can be reach for successful transmission of the triple play signals in passive optical networks without amplification or regeneration stages. This maximum reach is limited by the performance of the 1300 nm path that has higher losses at the fibre than the 1550 nm path, as it can be observed in Fig. 5 that the 1550 nm can achieve more than 100 km SSMF transmission.

The experimental results show up that signal with less than 14 dB signal-to-noise ratio (SNR) do not fulfil the wireless channel specifications. This can be observed in the received electrical spectrums shown in Fig. 6, where it can be appreciated that when the signals are less than the required limits, the SNR is very similar in both directions: 24.2 dB in the 1550 nm path after 101.8 km, and 23.5 dB in the 1300 nm path after 50.6 km SSMF. This confirms that, for the same PON reach, the 1300 nm path needs more launch power than the 1550 nm path.

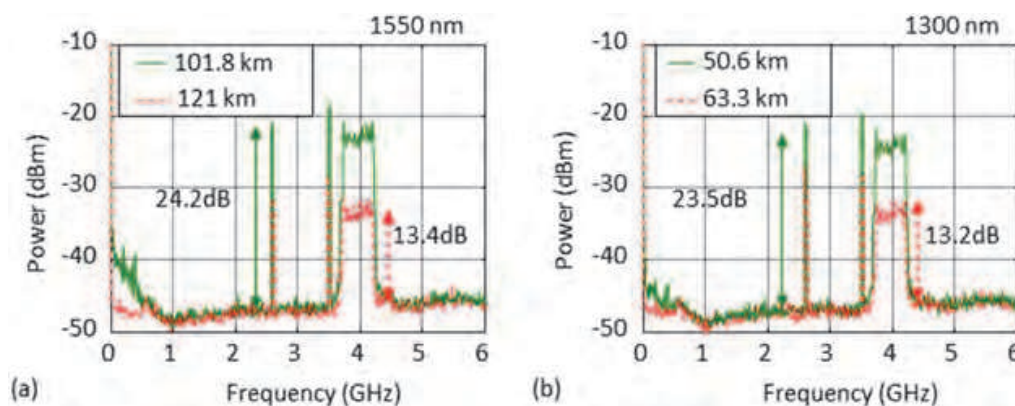


Fig. 6. Electrical spectrum examples and signal-to-noise ratio values working at (a) 1550 nm (after SSMF length of $L=101.8$ and 121 km) and (b) 1300 nm ($L=50.6$ and 63.3 km)

In the radio performance evaluation, the wireless path is included as depicted in Fig. 4. Fig. 7 shows the degradation of the received constellations at different points of the system. Clearly defined constellations and the EVM values below the regulation threshold indicate that a reliable opto-electronic link was established after 20.2 km SSMF and 3 m radio transmission in both directions.

4. UWB in the 60-GHz band

UWB technology is capable of providing multi-Gbit/s wireless communications. Maximum capacity in actual UWB devices is 480 Mbit/s per band as of WiMedia specification v1.2 (WiMedia, 2007; ECMA, 2008a). This gives an overall capacity of 6.72 Gbit/s per user when the

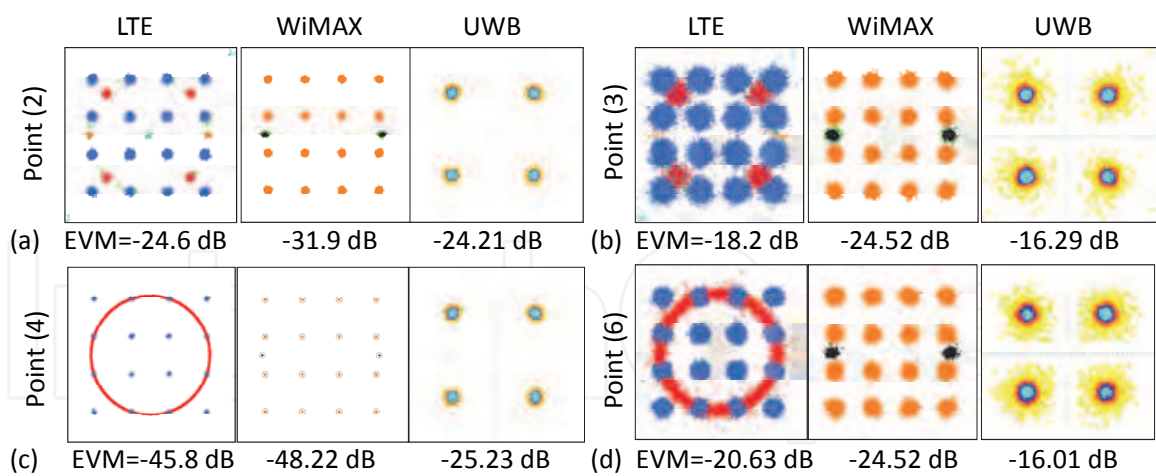


Fig. 7. Received constellations of LTE, WiMAX and UWB at different points of the experimental setup of Fig. 4: (a) input of the MZ [Point (1)] and (b) after 20.2 km SSMF and 3 m radio transmission [Point (3)] for the 1550 nm downstream path, and (c) radiated signal for upstream [Point (4)] and (d) after 20.2 km SSMF and 3 m radio for the 1300 nm upstream path

fourteen OFDM bands are combined. This capacity is supported in commercially-available single-chip UWB implementations (Alereon, 2009). The maximum theoretical UWB capacity would be achieved when the fourteen UWB bands are used bearing 1024 Mbit/s each as of WiMedia specification v1.5 (WiMedia, 2009a) giving 14.336 Gbit/s aggregated bitrate per user. Nevertheless, no commercial equipment to date supports this configuration. UWB capacity is further restricted outside the U.S. by regulation in force in each country due to coexistence issues (WiMedia, 2009b). UWB operation in the 60-GHz band is an open opportunity to provide potential data rates of >3 Gbit/s worldwide (Beltrán & Llorente, 2010a). 60-GHz radio is about to become easily available for consumer applications and permits secure multi-Gbit/s wireless communications with reach exceeding typical WPAN. UWB operation in the 60-GHz band is interesting for several reasons:

1. The unlicensed frequency range regulated for generic 60-GHz radio worldwide (within 57–66 GHz) can allocate very well the UWB bandwidth in current regulation (up to 7.5 GHz).
2. UWB is a mature technology with efficient software and single-chip solutions are also available. This permits UWB to be introduced in devices with specific space and power requirements, like mobile phones.
3. UWB is, in origin, a coexistence technology. Translating UWB technology from the 3.1–10.6-GHz band to the 60-GHz band opens the opportunity of coexistence with other wireless transmissions in the band.
4. UWB operation in the 60-GHz band permits extending the transmission reach by increasing the EIRP spectral density over -41.3 dBm/MHz , as in current UWB regulation worldwide, up to 13 dBm/MHz , as permitted in regulation in force in the band.

60-GHz UWB-over-fibre systems have been considered for two main applications. First, indoor distributed antenna systems (DAS) where 60-GHz UWB signals are distributed over fibre links from a central unit to remote antenna units (RAUs). This application is particularly interesting in interference-sensitive scenarios such as in-aircraft cabins (Beltrán & Llorente, 2010a). The fibre length in indoor DAS application is in the range of a

few hundred meters. In the second application, 60-GHz UWB signals are distributed from a central office through FTTH networks with further 60-GHz UWB wireless transmission in home (Beltrán & Llorente, 2010b; Beltrán et al., 2011). The approach in (Beltrán & Llorente, 2010b) can potentially integrate 60-GHz FTTH networks with 24-GHz and W-band optical networks exploiting chromatic dispersion of the fibre links. Cost-effective standard single-mode fibre (SSMF) is widely used in FTTH networks with distances up to approximately 40 km (Hülsermann et al., 2010). Recently-developed bend-insensitive single-mode fibre (BI-SMF) opens up an interesting opportunity for 60-GHz UWB-over-fibre to be deployed at indoor environments including in-home optical distribution as extension of the FTTH network. BI-SMF maintains the transmission properties of SSMF and is backwards compatible with SSMF. BI-SMF presents much lower bending loss than SSMF facilitating installation where tight corners and staples are required, thus reducing installation cost (Li et al., 2010). BI-SMF can also reduce the size of fibre installation and optical cabinets.

4.1 60-GHz radio

Millimetre-wave radio in the 60-GHz band is an open opportunity to support multi-Gbit/s services to multiple televisions and computers distributed throughout a dwelling/office replacing pervasive, HDMI and high-speed Internet cabling. 60-GHz transmission uses up to 9 GHz of frequency range available for unlicensed use over a short range. The increased free space loss in the 60-GHz band limits coverage area compared with links operating at lower frequencies enabling higher frequency reuse per indoor environment and secure communications (Daniels & Heath, 2007). In addition, the increased atmospheric attenuation in the 60-GHz band is the reason that 60-GHz links cannot cover the outdoor distances achieved by other millimetre-wave links without employing very large and very high gain antennas (Wells, 2009).

60-GHz frequency permits to employ directional and high-gain antennas with size much smaller than the lower frequency bands. This facilitates radio coexistence, provides multipath robustness, and makes it possible to have very small radios with multiple antennas solutions, enabling MIMO, beamforming and beam steering, which enhances the channel capacity and also supports non-line-of-sight (NLOS) communications.

International 60-GHz standards have been recently launched, leading to consumer electronics products, which are overviewed in Section 4.1.2.

4.1.1 Worldwide regulatory status

Current regulation in force for unlicensed use of 60-GHz radio worldwide is summarized in Table 1. The frequency range in the 60-GHz band can allocate very well the UWB bandwidth in current regulation (up to 7.5 GHz). Up to 9 GHz bandwidth is permitted in the EU and for indoor use in Australia, 7 GHz bandwidth is allocated in the U.S. and Canada, and 7 GHz in Japan (with 2.5 GHz maximum transmission bandwidths). There is a worldwide overlap in 5 GHz bandwidth in the range from 59 GHz to 64 GHz. In addition, 60-GHz UWB could operate at EIRP spectral density up to 13 dBm/MHz. This allows extending UWB range by increasing EIRP spectral density over -41.3 dBm/MHz provided that the increment in radio path attenuation at 60 GHz is compensated. Relatively high transmitter power employing shorter antennas allow for lower-power shorter-distance communications.

Country	Frequency Range	Usage	Maximum EIRP	Maximum transmitter power	Reference
EU	57 – 66 GHz	Indoor only	13 dBm/MHz 40 dBm	Not Defined	ETSI, 2009
		Indoor and Outdoor	-2 dBm/MHz 25 dBm		
Australia	57 – 66 GHz	Indoor only	43 dBm	13 dBm	ComLaw, 2009
U.S.	57 – 64 GHz	Not Defined	43 dBm peak (= 18 μ W/cm ² @ 3 m) 40 dBm average (= 9 μ W/cm ² @ 3 m)	27 dBm	FCC, 2008
Canada	57 – 64 GHz	Not Defined			IC, 2007
Japan	59 – 66 GHz	Not Defined	57 dBm	10 dBm	ARIB, 2005

Table 1. Current regulatory status in the 60-GHz band in major worldwide markets

4.1.2 Standardization status

A number of technologies capable of providing multi-Gbit/s wireless communications in the 60-GHz band targeting different markets have been proposed in the recent years. These technologies are summarized in Table 2. WirelessHD-based chips have been integrated into consumer electronic products such as TVs and wireless adapters. The operation of an ECMA-387-compliant link has also been demonstrated using a single-chip solution (ECMA, 2008b). In addition, the 802.11ad draft standard is expected to seamlessly integrate 60-GHz Wi-Fi into existing 2.4 GHz and 5 GHz Wi-Fi networks thus enabling next-generation tri-band radios.

Standard	Status	Theoretical maximum bitrate	Remarks	Reference
WirelessHD	v1.0 Jan. 2008 v1.1 May 2010	28 Gbit/s	Target WVAN applications: Cable replacement for HDMI, etc. OFDM only up to 10 Gbit/s in current market-available products	WirelessHD, 2010
ECMA-387	Dec. 2008	25.402 Gbit/s	Target WPAN applications single-carrier and OFDM	ECMA, 2008b
IEEE 802.15.3c	Oct. 2009	5 Gbit/s	Target WPAN applications single-carrier and OFDM	IEEE, 2009b
WiGig	July 2010	7 Gbit/s	Based on IEEE 802.11 target WLAN applications single-carrier and OFDM	WiGig, 2010

Table 2. Standards in the 60-GHz band

4.2 Integrated optical access and pico-cell transmission performance

Photonic generation of UWB signals can be a competitive solution supporting A/V streaming in the 60-GHz band due to the inherent coexistence characteristics of UWB, giving the benefit of seamless integration of optical transmission (access network) and radio provision (user pico-cell). Furthermore, optical frequency up-conversion at the central office is an interesting approach to reduce overall complexity and cost by centralized network management and simplified RAUs.

Fig. 8 shows a simple approach for photonic generation and integrated FTTH and radio transmission of 60-GHz UWB signals (Beltrán et al., 2011). At the central office, a 10-Gbit/s 1550-nm vertical-cavity surface-emitting laser (VCSEL) is employed for electro-optical conversion of baseband UWB signals. The optical UWB signal is modulated with a RF signal (local oscillator) in a Mach-Zehnder intensity modulator (MZM) to perform frequency up-conversion. The MZM is biased at the minimum transmission point to generate a double sideband with suppressed optical carrier signal. The two sidebands beat in the photodetector located at the RAU, yielding the UWB signal up-converted to the second harmonic of the local oscillator frequency. This up-conversion technique reduces RF power fading induced by chromatic dispersion of the fibre link (Schmuck, 1995) and the frequency requirement of the up-conversion devices at expense of reduced RF power (Ma et al., 2007). The baseband signal is also available after photodetection and it could be radiated meeting current UWB regulation. At the receiver, the received 60-GHz UWB signal is down-converted by electrical mixing with a local oscillator signal and digitized to be processed by digital signal processing (DSP).

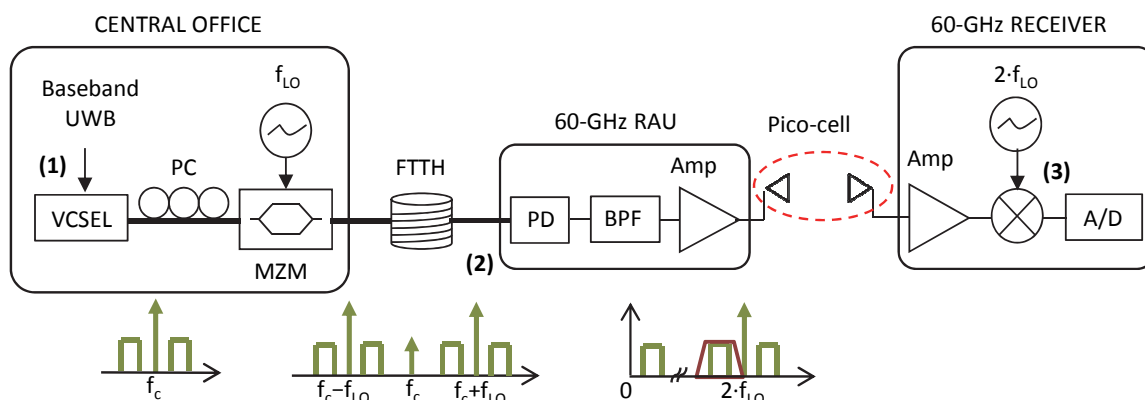


Fig. 8. Photonic generation and integrated FTTH and radio transmission of UWB signals in the 60-GHz band. PC: Polarization controller. LO: Local oscillator. PD: Photodetector. BPF: Band-pass filter. Amp: Amplification. A/D: Analogue-to-digital conversion

Performance of both impulse-radio UWB and standard OFDM UWB signals at 1.44 Gbit/s has been evaluated experimentally employing the scheme in Fig. 8. FTTH PON links employing optical amplification at the central office and 5-m wireless distance (directional antennas, line-of-sight path) is evaluated. Signals at point (3) in Fig. 8 are digitized at 40 GS/s.

4.2.1 OFDM UWB

An OFDM UWB signal fully-compliant with the ECMA-368 standard (ECMA, 2008a) is generated at point (1) in Fig. 8 employing commercially-available dongles. The signal comprises the Band #1, Band #2, and Band #3 employing the time-frequency codes TFC5, TFC6, and TFC7 as specified in the standard. Random data are modulated in each band

employing dual-carrier modulation (DCM) at 480 Mbit/s, thus providing an aggregated bitrate of 1.44 Gbit/s and a spectral efficiency of 0.91 bit/s/Hz.

The OFDM UWB signal is up-converted to 64.5 GHz and filtered at 58.125–61.875 GHz. The down-converted OFDM UWB signal at point (3) in Fig. 8 is demodulated employing commercially-available software. Fig. 9(a) shows performance in terms of EVM as a function of the optical power at point (2) in Fig. 8 for Band #1. Performance is evaluated for each OFDM UWB band and is limited by Band #1. Two optical transmission cases are considered: 40 km of SSMF and a 50-km dispersion-managed link comprising 25 km of SSMF and 25 km of inverse dispersion fibre (IDF) (Mukasa et al., 2006). The optical receiver sensitivity at $\text{EVM} < -17$ dB (ECMA, 2008a) is 1 dBm and -2 dBm for 40 km SSMF and 25-km SSMF+25-km IDF, respectively.

Minimum EVM for optical back-to-back (B2B) is limited by optical SNR. The chromatic dispersion of 40-km SSMF distorts the signal degrading the minimum EVM with respect to B2B. However, this degradation does not translate into penalty on optical receiver sensitivity. This is ascribed to gain in the fibre RF transfer function induced by the interaction of the chirp of the direct-modulated VCSEL with fibre chromatic dispersion (Wedding, 1994). The gain improves SNR limited by electrical noise at low received optical power, thus improving EVM. The gain in the power level as well as signal distortion for 40 km of SSMF with respect to B2B can be verified in Fig. 2(b). In addition, 25 km of IDF compensates for RF power fading induced by 25-km SSMF dispersion. The optical receiver sensitivity improvement for 25-km SSMF+25-km IDF with respect to B2B in Fig. 2(a) is again ascribed to the interplay between VCSEL chirp and residual dispersion of the dispersion-managed link. Fig. 2(c) shows examples of DCM-OFDM constellation diagrams at different EVM values.

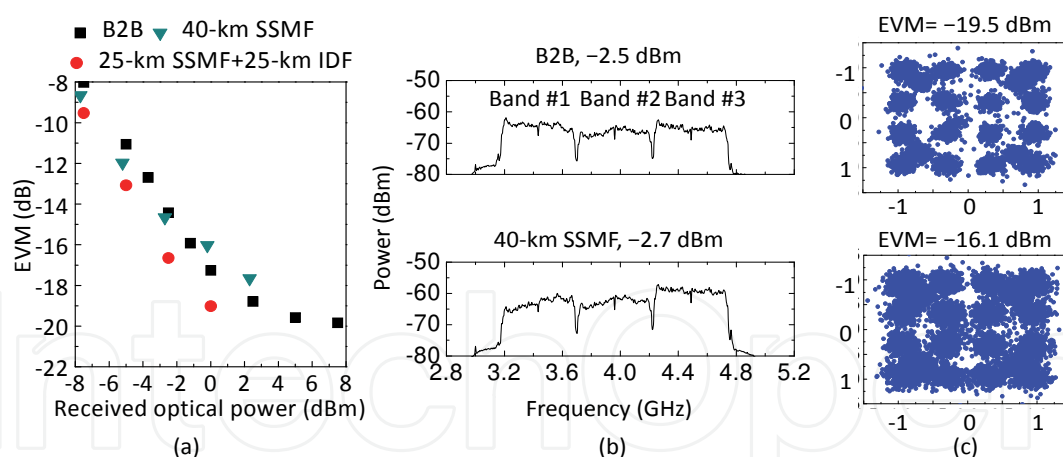


Fig. 9. Performance of the 60-GHz OFDM UWB signal measured at point (3) in Fig. 8 integrating optical and 5-m wireless transmission. (a) EVM for Band #1. (b) RMS spectrum (resolution bandwidth: 5 MHz). (c) Constellation diagrams for Band #1

4.2.2 Impulse-radio UWB

An impulse-radio UWB signal is generated by an arbitrary waveform generator (AWG) at 23.04 GS/s at point (1) in Fig. 8. The UWB pulse is a fifth-order derivative Gaussian shape comprising a single band in good compliance with the UWB EIRP spectral density mask in current regulation (FCC, 2002), as shown in Fig. 10. A pseudo random binary sequence (PRBS) with a word length of $2^{11}-1$ is modulated employing bi-phase modulation (binary

phase-shift keying BPSK) at 1.44 Gbit/s. Compared with other modulation formats such as on-off keying (OOK) and pulse position modulation (PPM), BPSK modulation reduces spectral peaks at multiples of the data rate, thus providing better power efficiency under the UWB mask. Power efficiency is critical to extend UWB reach. This system has potential ranging capabilities taking advantage of the excellent accuracy of impulse-radio UWB when short pulses are employed.

The impulse-radio UWB signal is up-converted to 64.66 GHz and filtered at 58.125–61.875 GHz. The down-converted impulse-radio UWB signal at point (3) in Fig. 8 is demodulated employing custom DSP. The DSP comprises re-sampling, low-pass filtering, matched filtering with the original UWB pulse shape, bit synchronization and calculation of the optimum decision threshold. Fig. 10 shows performance in terms of bit error rate (BER) as a function of the optical power at point (2) in Fig. 8. Two optical transmission cases are considered: 25 km of SSMF (5.2-dB loss) and 40 km of SSMF (7.7-dB loss). The optical receiver sensitivity at $\text{BER} < 2.2 \cdot 10^{-3}$ (BER limit including forward error correction) is -12.5 dBm and -15.6 dBm, respectively. The maximum received optical power in the experiment is 10 dBm so that the optical power budget apart from fibre loss is 17.3 dB and 17.9 dB, respectively. Fig. 10 shows examples of BPSK eye diagrams.

BER is limited by electrical noise. Decreasing the received optical power further increases BER due to the reduction in signal-to-noise ratio (SNR). In addition, BER improves after optical transmission with respect to optical B2B. This is ascribed to gain in the fibre RF transfer function induced by the interaction of the chirp of the directly-modulated VCSEL with fibre chromatic dispersion (Wedding, 1994), like for the OFDM UWB signal.

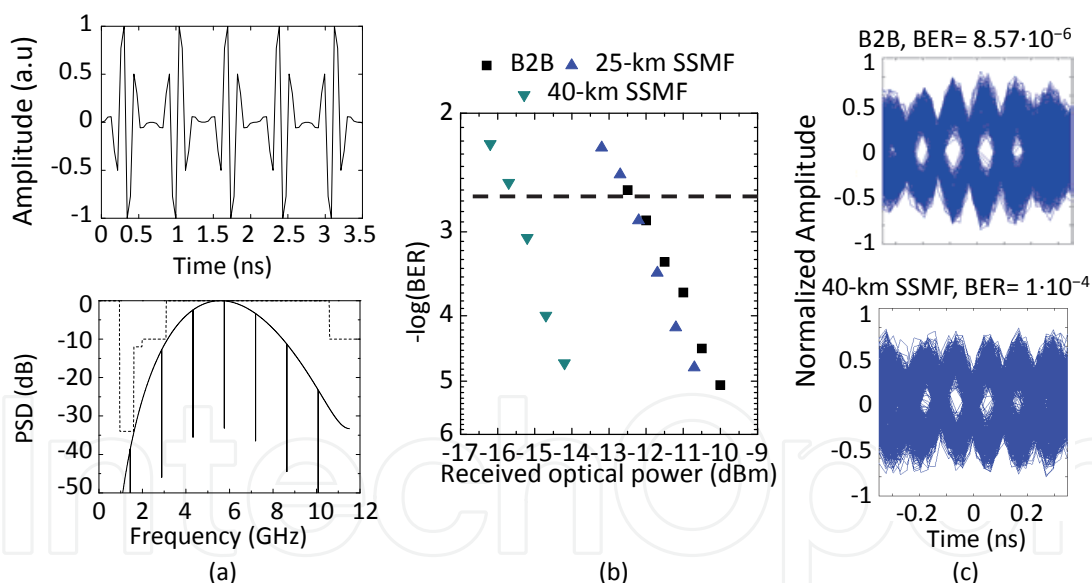


Fig. 10. (a) Impulse-radio UWB signal applied to the AWG. The UWB EIRP spectral density mask in current regulation (FCC, 2002) is shown via a dashed line; Performance of the 60-GHz impulse-radio UWB signal measured at point (3) in Fig. 8 integrating optical and 5-m wireless transmission: (b) BER. The forward error correction limit of $2.2 \cdot 10^{-3}$ is shown via a dashed line. (c) Eye diagrams

5. Conclusion

In this chapter, UWB radio-over-fibre in FTTH access networks with PON architecture is proposed as a next-generation optical access solution. Optical and radio transmission

performance is investigated employing commercially-available UWB transmitters, fully compliant with the ECMA-368 standard. Standard OFDM UWB transmission is reported in FTTH PON access including radio transmission.

The coexistence characteristics of UWB with WiMAX and LTE radio, the most limiting impairment in next-generation optical access, are reported considering bidirectional full-standard triple-play provision. Successful full-duplex provision of triple-play services via UWB in coexistence with standard OFDM-based WiMAX and LTE radio is possible up to 20.2 km of SSMF including 3 m radio propagation.

UWB operation in the 60 GHz radio band has been also proposed as an interesting approach. The 60 GHz UWB systems proposed could operate in a dual 3.1–10.6 GHz/60 GHz configuration if desired. 60-GHz band operation would re-use and extend UWB technology in terms of range and flexibility, and is the focus of this work.

Finally, the performance of the two mainstream UWB implementations -dual-carrier modulation orthogonal frequency division multiplexing (DCM-OFDM) and binary phase-shift keying impulse radio modulation- is also described in this chapter. The results presented permit, from an application point-of-view, to select a given UWB implementation depending on network reach and system complexity desired.

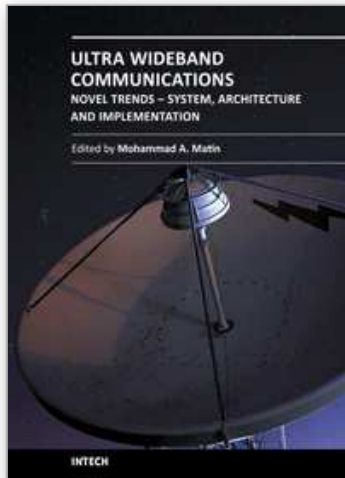
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